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Research Article

Physio-Chemical Analysis of Turmeric Rhizomes (Curcuma Longa L.) Preserved Through Non-Thermal Technique: Electrohydrodynamic Drying

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ABSTRACT
The preservation of turmeric rhizomes (*Curcuma longa L.*) through non-thermal drying techniques has gained significant attention due to its ability to retain bioactive compounds and overall quality. This study investigates the physio-chemical properties of turmeric rhizomes preserved using Electrohydrodynamic (EHD) drying at varying electrode distances (7 cm, 5 cm, and 3 cm) under a voltage of 24 kV, 17 kV and 14 kV respectively. The effects of EHD drying on porosity, shrinkage ratio, rehydration ratio, colour attributes, and curcumin content were evaluated. The results showed that porosity remained consistent across all treatments (65.3–65.49%), indicating uniform drying. Shrinkage ratios ranged from 67.133% to 68.531%, with no significant differences observed, suggesting minimal structural damage during drying. The rehydration ratio was significantly influenced by electrode distance, with the highest ratio observed at 3 cm (313), indicating better water retention and texture. Colour analysis revealed that the dried turmeric retained a colour closest to the fresh sample at 3 cm, while drying at longer electrode distances (5 cm and 7 cm) resulted in increased yellowness and reduced redness. Curcumin content was best preserved at the 3 cm distance, with a significant reduction observed at higher distances. Overall, EHD drying proved to be an effective non-thermal method for preserving the quality, colour, and bioactive compounds of turmeric rhizomes, particularly at shorter electrode distances, offering a promising alternative to traditional thermal drying methods for maintaining the nutritional and therapeutic properties of turmeric.

Keywords: Electrohydrodynamic drying, Curcumin, Physio-chemical analysis, Rehydration, Electrode distance

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INTRODUCTION

Curcumin is active ingredient of Turmeric (*Curcuma longa*) and it holds promise in addressing modern health challenges. Research indicates its potential to reduce risks associated with chronic diseases such as cancer, cardiovascular complications, and neurological disorders like Alzheimer's. However, the naturally low bioavailability of curcumin stemming from its rapid metabolism and limited absorption presents a hurdle. While the full extent of curcumin's mechanisms remains under investigation, the inclusion of turmeric in daily nutrition offers a practical approach to harnessing its benefits.

Whether as a culinary spice, a traditional remedy, or a modern supplement, turmeric continues to exemplify the harmonious blend of ancient wisdom and contemporary science, underscoring its role in promoting holistic health and well-being. Turmeric (*Curcuma longa*), a herb from the Zingiberaceae family, has long been revered for its versatile rhizomes. These underground stems serve as a cornerstone in traditional cuisines and ancient medicinal systems. The plant owes its characteristic golden hue and therapeutic value to curcumin, a powerful polyphenolic compound. Curcumin has garnered significant attention for its multifaceted bioactivities, including potent antioxidant capabilities that neutralize free radicals, anti-inflammatory effects that mitigate cellular damage, and antimicrobial properties that combat harmful pathogens.

Electrohydrodynamic (EHD) drying represents a cutting-edge advancement in food processing technology, offering a transformative approach to dehydration processes. Unlike conventional drying methods that rely primarily on thermal energy, EHD drying employs high-intensity electric fields to accelerate moisture removal from food products. This non-thermal mechanism not only reduces energy consumption but also minimizes thermal degradation, ensuring superior retention of nutritional and sensory qualities.

The principles underlying EHD drying are rooted in the interaction between electrical forces and fluid dynamics. The application of an electric field generates ionic winds and enhances convective moisture transfer, resulting in significantly faster drying rates. This technique has demonstrated remarkable efficiency in preserving heat-sensitive bioactive compounds, textures, and colours, making it a promising alternative for processing high-value food products.

Drying is an essential operation in food processing, critical for extending shelf life, enhancing storage stability, and retaining the nutritional integrity of food products. Conventional drying methods, including convective, conductive, and radiant techniques, have been widely utilized in the food industry. Despite their extensive use, these traditional methods often face challenges such as prolonged drying durations, significant nutrient degradation, and compromised product quality. Compared to traditional methods like hot-air drying or freeze-drying, EHD drying presents distinct advantages, including lower energy inputs, shorter processing times, and reduced operational costs. Furthermore, its ability to maintain the structural integrity and quality of the dried product has been highlighted in various studies, emphasizing its potential to revolutionize industrial drying applications.

Electrohydrodynamic (EHD) drying has emerged as an innovative and effective alternative to traditional drying techniques, addressing key challenges associated with mass transfer limitations. By employing an electric field, this method induces the movement of charged particles, creating a phenomenon known as the electrohydrodynamic effect. This effect generates airflow at the food-air interface, enhancing mass transfer and significantly accelerating the drying process. As a result, EHD drying offers reduced drying times and improved energy efficiency, making it highly attractive for large-scale food processing applications.

Numerous studies have demonstrated the advantages of EHD drying over conventional methods. For example, research conducted by Chen et al. (2016) on apple slices revealed that EHD drying achieved a moisture removal rate of 10.5% per hour, compared to only 7.6% per hour using hot air drying. This substantial improvement not only underscores the potential of EHD drying to enhance processing efficiency but also highlights its capability to handle high-throughput operations without compromising product quality. Such advancements position electrohydrodynamic drying as a superior alternative for modern food preservation and processing techniques.

Furthermore, electrohydrodynamic drying offers unique advantages in terms of preserving product quality. Traditional drying methods often result in undesirable changes to food properties, including shrinkage, colour degradation, and nutrient loss. Conversely, research studies have demonstrated that electrohydrodynamic drying minimizes these detrimental effects. For example, a study conducted by Smith et al. (2019) on the drying of strawberries using electrohydrodynamic drying showed preserved colour, texture, and vitamin C content compared to other drying methods such as hot air drying and freeze drying.

Electrohydrodynamic (EHD) drying offers unparalleled versatility through precise control over process parameters, making it highly adaptable to a wide range of food products. By enabling adjustments to electric field intensity, frequency, and waveform, this technique allows for fine-tuning to achieve optimal drying outcomes. Such control is particularly beneficial for heat-sensitive foods, ensuring minimal thermal degradation while preserving critical sensory and nutritional qualities. For instance, Yang et al. (2018) demonstrated the advantages of vacuum-assisted EHD drying for blueberries, reporting enhanced retention of anthocyanin pigments, which contribute significantly to the fruit's antioxidant properties.

When compared to conventional drying methods, EHD drying consistently demonstrates superior performance in terms of efficiency and quality. Liu et al. (2020) highlighted the advantages of EHD drying over hot air drying, noting faster water removal rates, reduced energy consumption, and improved product quality. Additionally, the study emphasized the enhanced drying uniformity achieved with EHD drying, resulting in products with consistent texture and quality. These findings underscore the potential of EHD drying as a transformative solution in food processing, combining efficiency, adaptability, and the ability to maintain high-quality standards.

Electrohydrodynamic (EHD) drying stands out as an innovative and transformative advancement in food processing technology, offering significant advantages over conventional drying methods. Its ability to achieve faster drying rates, superior energy efficiency, and enhanced preservation of nutritional and sensory qualities makes it an attractive solution for modern food processing challenges. The precise control over drying parameters provided by this technique ensures reduced nutrient loss and improved retention of key product attributes, particularly in heat-sensitive foods. This technique also helps preserve micronutrients in food. Srivastava et al. (2023) observed significant retention of β-carotene in carrot samples.

Comparative studies consistently highlight the superior performance of EHD drying in terms of efficiency, uniformity, and quality retention, positioning it as a potential breakthrough in the industry. As ongoing research continues to refine its mechanisms and applications, EHD drying holds considerable promise for widespread adoption in commercial food processing. Its integration into industrial practices could pave the way for improved food quality, extended shelf life, and more sustainable production processes, reshaping the future of food preservation.

MATERIALS AND METHODS

Materials

Turmeric rhizomes were sourced from a local supplier in Anand, Gujarat, India. The rhizomes were thoroughly washed and cleaned to remove any soil and contaminants, followed by surface moisture removal using blotting paper. The prepared turmeric samples were then stored in sealed zip pouches at ambient temperature 28°C until further processing. The initial moisture content of the turmeric was determined to be 89.74% ± 1.32 (w.b.), using the standard hot air oven method (AOAC, 1999). The turmeric rhizomes were then sliced using an adjustable stainless-steel slicer into 2 ± 0.1 mm thick slices, with an average size of 45 × 20 mm. The slices were elliptical in shape, with the major axis measuring 45 ± 0.81 mm and the minor axis measuring 20 ± 0.45 mm. No pre-treatment was applied to the turmeric slices prior to further processing.

Experimental Setup

The experimental setup for the electrohydrodynamic (EHD) dryer, along with all associated components, is depicted schematically in Fig. 1. The Experimental Setup Sketch of Electrohydrodynamic Dryer is shown in Fig. 2. The main elements of the setup include a high voltage generator (High Voltage-India, Bangalore), drying chamber, heating chamber, blower, sample holder, anode and cathode electrodes, and sharp needle electrodes. The drying chamber was constructed using a metal box, coated with fire-resistant matte powder. The inner dimensions of the EHD drying chamber were 475 × 475 × 450 mm.

Two hardened SS 316 plates, each 4 mm thick, were used as the anode and cathode. Sharp pins, 20 mm in length, were welded onto the anode plate prior to hardening. The design of the dryer was optimized based on trial experiments and insights from existing literature, with the following parameters being standardized: AC or DC voltage, the distance between the electrodes, voltage per centimetre supplied to the electrodes, the type of electrode plates or pins, the number of pin electrodes per square centimetre, the distance between pin electrodes, the temperature of the air during drying, and the air velocity during drying.

The EHD dryer was operated at a variable AC voltage range of 0 to 50 kV. Thin, sharp sewing needle electrodes were used, with a variable distance between them ranging from 3 to 7 cm. The dryer operated at ambient temperature using air convection, with blower incorporated into the system during the experiments.

We conducted an experiment to assess the performance of an electrohydrodynamic (EHD) dryer for drying fresh turmeric rhizomes. The experimental setup comprised an EHD dryer prototype, a heater with adjustable temperature control ranging from ambient to 60°C, an energy meter to monitor power consumption, and a drying chamber to house the samples.

From the findings of several researchers, the following key parameters were established and incorporated into the design of the EHD dryer:

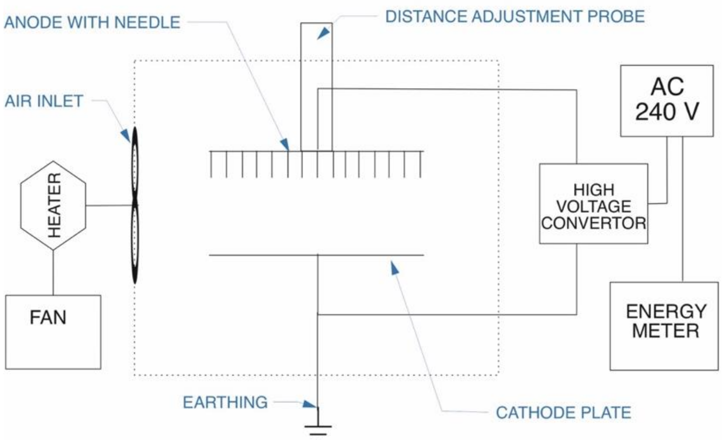

Fig (1) Schematic Diagram of Electrohydrodynamic Dryer

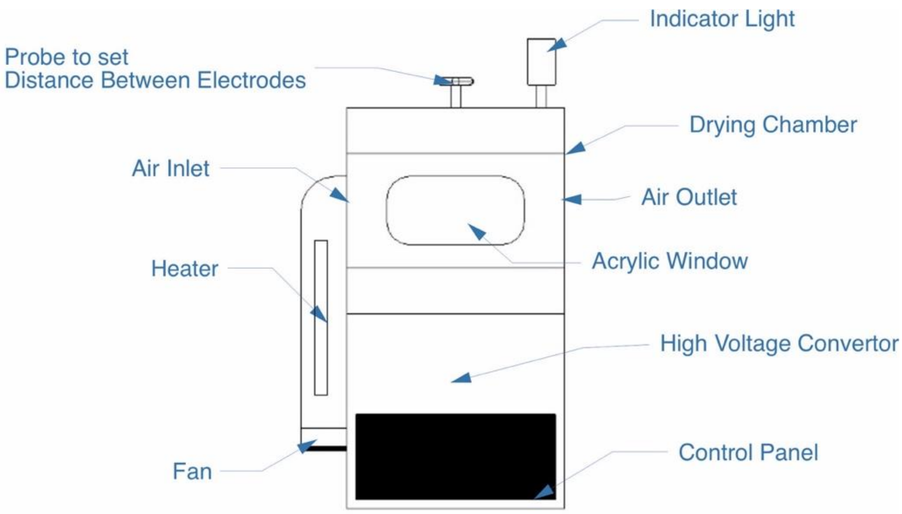

Fig (2) Experimental Setup Sketch of Electrohydrodynamic Dryer

Table 1.1: Specification of EHD dryer

Parameters	**Specifications**
AC or DC voltage	AC
Distance between two electrodes	Variable from 3 to 10 cm
Voltage supplied to electrodes	0 – 50 kV
Plate or needle electrodes	Needle electrodes
Type of pin/needle electrodes	Thin, Sharp, Sewing needle
Number of pin/needle electrodes	Multiple and arranged in 2 x 2 cm
Temperature of air during drying	Ambient
Air velocity during drying	Adjustable from 0 – 0.5 m/s

Drying experiments

Turmeric rhizomes were weighed (20-25 g) and placed on the grounded electrode (cathode) of the EHD dryer. Experiments were conducted at combinations of temperature between 30-55 °C (combinations standardized with IBM SPSS) with a relative humidity of 33 ± 3%. The drying behavior of turmeric rhizomes in the EHD dryer was studied at three different electrode distances (3, 5, and 7 cm) under constant voltages (24 kV, 17 kV, 14 kV) and frequency (50 Hz). The weight of the turmeric rhizome samples was recorded periodically at 10-minute intervals. All experiments were performed in triplicate.

The drying process was initiated by placing the turmeric rhizomes inside the drying chamber, ensuring selected airflow and exposure. The desired drying temperature was set on the heater, and the electrohydrodynamic dryer was activated. We monitored the readings from the energy meter to accurately measure power consumption during the drying process. Throughout the drying procedure, the progress was closely observed, with attention to factors such as drying time and any changes in the physical properties or moisture content of the turmeric rhizomes. Adjustments to the temperature, airflow, and other relevant parameters were made as necessary to optimize the drying process and improve overall efficiency.

Physio-chemical analysis of dried turmeric slices was performed by measuring Bulk density, true density, Porosity, Shrinkage ratio, rehydration ratio, colour, water activity and curcumin retention.

1.1 Bulk Density

The bulk density of turmeric slices is defined as the mass of the slices per unit volume, incorporating both the solid material and the interstitial voids (air spaces) present between the slices. This parameter is crucial for evaluating the textural properties and packing characteristics of the slices, which in turn affect their processing, storage, and packaging behaviors. Bulk density is influenced by various factors, including the drying conditions, moisture content, and the dimensional characteristics (size and thickness) of the turmeric slices. Therefore, understanding and controlling bulk density is vital for ensuring the quality, cost-efficiency, and durability of dried food products throughout their supply chain journey.

Bulk Density (ρb) was calculated using the formula:

$$\rho_b = \frac{m}{V} - - - - - - - - (1)$$

Where, *m* is the mass of the sample and *V* is the volume of the sample.

1.2 True Density

True density represents the intrinsic density of dried food, reflecting the material's actual mass relative to its volume, excluding any voids or air gaps within its structure. Unlike bulk density, which accounts for the space occupied by both the material and the air between particles, true density provides a more precise measurement of the material's fundamental composition and structure. By accurately determining true density, we can gain valuable insights into the inherent properties of the dried food, such as its molecular arrangement, composition, and overall solidity, independent of its porosity.

True Density (ρt) can be calculated using the formula:

$$\rho_t = \frac{m}{V'} - - - - - - - - (2)$$

Where *m* is the mass of the sample and *V′* is the volume of the sample excluding voids.

1.3 Porosity

Porosity refers to the proportion of voids or gaps present within the structure of dried food material. Understanding porosity is crucial for assessing the structural integrity, texture, and overall quality of dried products. The porosity of a material plays a key role in determining its rehydration kinetics, texture, and sensory attributes. A material with lower porosity typically has a more compact structure with fewer void spaces, which facilitates quicker rehydration when water is reintroduced. This is because water molecules encounter fewer barriers as they penetrate the material, leading to faster moisture absorption. Additionally, a denser structure with lower porosity helps preserve the texture of the food upon rehydration, resulting in a more desirable product that closely resembles its fresh counterpart.

The porosity of all dried sample was calculated using following formula:

$$p_{(\%)} = \left(1 - \frac{\rho_b}{\rho_t}\right) X\ 100 - - - - - - - - (3)$$

1.4 Shrinkage Ratio

Shrinkage is an inherent outcome of the drying process, and it can significantly influence the appearance, texture, and nutrient retention of dried foods. Monitoring the shrinkage ratio is essential for optimizing drying conditions, as it helps minimize structural damage and ensures that the final product retains its desired qualities. The shrinkage ratio (S) quantifies the degree to which the size or volume of the food material decreases during drying, providing valuable insight into the physical changes that occur. This parameter is particularly important for evaluating alterations in the physical dimensions, such as the reduction in size, and the overall visual appeal of dried food products. Excessive shrinkage can lead to undesirable texture changes, such as brittleness or toughness, and may result in the loss of important nutrients. By carefully controlling shrinkage, researchers can improve the quality, texture, and nutritional value of dried foods, while enhancing their marketability.

Shrinkage Ratio (S) was determined using the equation:

$$S = \left(\frac{L_0 - L_d}{L_d}\right) - - - - - - - - (4)$$

Where, L_0 is the initial length of the sample and L_d is the length of the dried sample.

1.5 Rehydration Ratio

The rehydration ratio (R) is a key metric used to assess the ability of dried food to absorb moisture and rehydrate when exposed to water. This parameter is crucial in evaluating the reconstitution properties, texture, and sensory attributes of dried foods. A higher rehydration ratio indicates that the food can effectively uptake and retain moisture, allowing the final product to closely mimic its fresh counterpart in terms of taste, texture, and visual appeal. Foods with a superior rehydration ratio tend to maintain their original quality after rehydration, leading to improved consumer satisfaction. Moreover, rehydration properties directly influence the culinary usability of dried foods, making this parameter an important consideration for both food manufacturers and consumers seeking high-quality, versatile products.

Rehydration Ratio (*R*) was calculated as:

$$R = \left(\frac{W_r - W_d}{W_d}\right) - - - - - - - - (5)$$

Where *Wr* is the weight of the rehydrated sample and *Wd* is the weight of the dried sample.

1.6 Analysis of Color

In the analysis of dried samples, considerable attention was given to evaluating their colour properties using a Konica Minolta CR-400 colorimeter, a highly advanced and precise instrument for colour measurement. To ensure the accuracy and reliability of the readings, the colorimeter was calibrated rigorously in line with the manufacturer's guidelines before each measurement session. This careful calibration process ensured consistency and precision throughout the entire analysis.

Each dried sample underwent a thorough colour measurement procedure, with the colorimeter recording L*, a*, and b* values—representing lightness, the green-red axis, and the blue-yellow axis of colour, respectively. To mitigate potential variability and ensure the reliability of the data, five measurements were taken per sample. This approach not only provided a comprehensive dataset but also allowed for the calculation of standard deviations (dL, da, db), offering valuable insights into the consistency and uniformity of the colour properties within each sample group.

The data obtained from these measurements were then used to calculate additional color attributes, including chroma (C*), hue angle (h°), and total colour difference (ΔE), based on established formulas and colour difference equations. These parameters offered a deeper understanding of the colour intensity, hue direction, and perceptible differences between the dried samples. Chroma and hue angle highlighted the depth and tone of the colour variations, while the total colour difference enabled a direct comparison between samples, making it possible to assess any noticeable changes in colour properties.

$$C^* = \sqrt{a^{*2} + b^{*2}} - - - - - - - - (6)$$

$$h^o = tan^{-1} \frac{b^*}{a^*} - - - - - - - - (7)$$

$$\Delta E = \sqrt{\Delta a^{*2} + \Delta b^{*2} + \Delta c^{*2}} - - - - - - - - (8)$$

1.7 Analysis of water activity

Water activity (a_w) is a crucial parameter in drying analysis, offering significant insights into the stability, shelf life, and microbial safety of dried products. In this study, the water activity of all samples was carefully measured using a ROTRONIC HW4 water activity meter, a specialized and highly accurate instrument known for its precision in analysing water activity. To ensure reliability and consistency, each sample underwent three independent measurements, and the average value was calculated to provide the most accurate assessment.

Water activity (a_w) is the ratio of the vapor pressure of water in a sample to the vapor pressure of pure water at the same temperature. It is a key indicator of the amount of water available in a product for microbial growth and chemical reactions. Understanding the water activity of dried products is critical because it affects not only microbial stability but also various quality attributes, including texture and rehydration properties. One of the most important roles of water activity in drying analysis is its relationship with microbial stability. Microorganisms, such as bacteria, moulds, and yeasts, rely on water for growth and reproduction. When water activity falls below a certain threshold, microbial growth is inhibited, thus prolonging the shelf life and ensuring the safety of the product. By measuring water activity, we can assess whether the dried product is safe for long-term storage without the risk of microbial contamination.

In addition to its impact on microbial stability, water activity plays a pivotal role in determining the physical attributes of dried foods, such as texture, crispness, and rehydration capacity. Lower water activity levels generally result in improved texture and crispness, which are desirable characteristics in many dried food products. On the other hand, higher water activity may lead to a softer, less desirable texture and increased susceptibility to moisture-related spoilage, such as caking or clumping.

Moreover, water activity is a key factor in the chemical stability of dried products. It influences various chemical reactions, including oxidation and enzymatic processes, which can alter the flavour, nutritional content, and overall quality of the product. By controlling water activity during the drying process, we can limit these detrimental reactions, preserving the integrity and flavour profile of the product.

1.8 Analysis of Curcumin Content

In the detailed process of assessing curcumin content in dried turmeric samples, a systematic and precise methodology was employed to ensure reliable and accurate results. The initial step involved the careful preparation of the dried samples, which were ground into a fine powder to achieve uniformity and consistency. To preserve the integrity of the curcumin, which is highly sensitive to light and moisture, every precaution was taken to prevent exposure to these elements during sample preparation.

The next stage involved curcumin extraction using a solvent (ethanol), known for its high solubility for curcumin. To optimize the extraction efficiency, techniques such as maceration or sonication were used to ensure maximum curcumin yield from the dried turmeric samples. This step was critical to obtaining accurate and representative results of the curcumin content.

Once extraction was complete, the curcumin content was quantified using UV spectrophotometry. A UV-visible spectrophotometer was employed to measure the absorbance of the extracted curcumin solution at a wavelength of 420 nm, where curcumin exhibits a strong absorbance peak. To enable precise quantification, a calibration curve was constructed using standard curcumin solutions of known concentrations. By measuring the absorbance of these standard solutions at various concentrations, a reliable calibration curve was developed, which then allowed the curcumin content in the turmeric samples to be determined based on their corresponding absorbance values.

The data obtained were statistically analysed, calculating the mean values and standard deviations to assess the consistency and reliability of the curcumin measurements. This analysis ensured that the results were both accurate and reproducible.

The significance of curcumin content measurement in dried turmeric samples extends beyond simple quantification. It is a critical quality control parameter that guarantees the consistency, authenticity, and potency of dried turmeric products. By quantifying curcumin levels, we can verify the product's quality, assuring consumers and stakeholders of its effectiveness and reliability. Moreover, the measurement of curcumin content provides important insights into the nutritional profile of dried turmeric. As curcumin is known for its antioxidant and anti-inflammatory properties, quantifying its presence helps to evaluate the potential health benefits of turmeric-based products, whether for dietary or therapeutic uses. This data is essential for the development of products that meet specific health-promoting criteria.

Additionally, understanding the impact of drying processes on curcumin retention is vital for optimizing drying techniques to minimize curcumin degradation. By studying how different drying parameters affect curcumin levels, we can refine their methods to preserve curcumin and enhance the bioactivity of dried turmeric products. This knowledge ultimately aids in the creation of superior-quality turmeric products that retain their beneficial properties for consumers.

RESULTS AND DISCUSSION

2.1 Bulk Density and True Density

The results shows the effects of distance, voltage, air velocity, and other parameters on bulk and true density. At the longest distance (7), with the highest applied voltage (24 kV) and an air velocity of 0.5, the true density was found to be 1108.45 kg/m³, and the bulk density was 384.59 kg/m³, which were the highest among the trials. As the distance decreased, there was a slight increase in true density, reaching 1113.70 kg/m³ and 1117.41 kg/m³ at the shorter distances, although bulk density remained nearly constant across all trials. This suggests that decreasing the distance slightly influences the internal structure or compaction of the material, but the overall packing density remains stable.

The voltage applied during the trials also had some impact. The highest voltage (24 kV) showed the highest bulk density, while a decrease in voltage resulted in a slight reduction in bulk density. However, the change in true density was minimal, indicating that voltage may influence the drying process but does not significantly affect true density. he values are elaborated in detail in Table 2.1.

Air velocity was held constant for two of the trials, while the other had a higher air velocity (0.5). The increased air velocity was associated with a slightly higher bulk density, but it did not significantly impact the true density. Temperature was consistent at 30°C throughout all trials, suggesting that it did not play a significant role in the observed variations. Martynenko and Kudra (2018) demonstrated how varying parameters, such as electrode design, air velocity, and power intensity affect bulk and true density during EHD drying. Their findings align with current research.

2.2 Porosity

The porosity percentages of dried turmeric samples at electrode distances of 7 cm, 5 cm, and 3 cm were 65.3%, 65.34%, and 65.49%, respectively. The porosity of the dried turmeric slices showed minimal variation across the different electrode distances. This slight difference indicates that the electrohydrodynamic (EHD) drying process, regardless of the electrode distance, maintained similar porosity in the turmeric samples. The values suggest a relatively consistent structural property of the samples, which may have been influenced by the corona wind's ability to penetrate and create porous structures within the samples. For a full breakdown of the values, see Table 2.1. The minimal change in porosity further implies that the EHD drying process under the specified voltage (24 kV, 17 kV and 14 kV) was effective in maintaining a uniform drying environment. Srivastava et al. (2023) demonstrated that EHD drying is effective in retaining the structural integrity of dried carrot slices. Their experiments revealed that porosity levels remained consistent across varying drying voltages, attributed to the balanced drying environment created by EHD technology.

2.3 Shrinkage Ratio

The shrinkage ratio of dried turmeric slices at electrode distances of 7 cm, 5 cm, and 3 cm was 67.133%, 67.276%, and 68.531%, respectively. The shrinkage ratio did not exhibit significant differences between the different electrode distances, indicating that the shrinkage behavior of the dried turmeric slices remained consistent despite changes in electrode distance. The slight increase in shrinkage at the smallest electrode distance (3 cm) may be attributed to the more intense corona wind effect, which could have led to greater moisture removal from the turmeric slices. However, the differences in shrinkage were minimal, suggesting that the structural network of the turmeric slices and the even distribution of moisture under the corona wind played a crucial role in maintaining similar shrinkage levels. This finding aligns with results reported by Bai et al. (2012), Esehaghbeygi and Basiry (2011), and Esehaghbeygi et al. (2014). The complete set of values can be found in Table 2.1.

2.4 Rehydration Ratio

The rehydration ratios of the turmeric slices at electrode distances of 7 cm, 5 cm, and 3 cm were 306, 313, and 312 respectively. The rehydration ratio decreased as the distance between the electrodes increased, with the highest rehydration ratio observed at the 3 cm electrode distance. This can be attributed to the more significant penetration of corona wind at smaller electrode distances, which enhanced the formation of a porous structure in the turmeric slices. At larger electrode distances (5 cm and 7 cm), the corona wind had less penetration, limiting the development of porosity, which in turn led to a lower rehydration ratio. The results were statistically significant ($P < 0.01$), indicating that the electrode distance had a substantial impact on the rehydration properties of the turmeric slices. This finding is consistent with the research by Yu et al. (2018) and Yang and Ding (2016), who also reported the influence of electrode distance on the rehydration ratio. Table 2.1 presents the comprehensive values.

2.5 Colour

The colour attributes of dried turmeric slices were assessed under varying electrohydrodynamic (EHD) drying conditions, specifically at electrode distances of 7 cm, 5 cm, and 3 cm. The results revealed distinct changes in the colour properties of the turmeric slices as a function of the electrode distance. At the 7 cm electrode distance, the turmeric slices exhibited the highest lightness ($L^* = 60.73$) and chroma ($C^* = 60.498$) values, indicating a brighter and more intense colour. However, as the electrode distance decreased, both lightness and chroma values declined, with the lowest values observed at the 3 cm distance ($L^* = 58.58$, $C^* = 54.411$). Despite this reduction in colour intensity, the hue angle (h°) remained relatively stable across all distances, ranging from 1.14 to 1.179, which suggests that the general colour tone of the turmeric (yellow-orange) was consistently maintained.

The total colour difference (ΔE), which quantifies the overall change in colour from the fresh sample, was lowest at the 3 cm electrode distance ($\Delta E = 2.388$), indicating that the dried turmeric slices at this distance retained a colour closer to that of the fresh turmeric. In comparison, the colour difference increased at the 5 cm ($\Delta E = 2.454$) and 7 cm ($\Delta E = 2.573$) distances, suggesting that the colour of the turmeric slices became more altered as the distance between the electrodes increased.

These findings highlight the influence of electrode distance on the colour preservation of turmeric slices during EHD drying. The shorter electrode distances (3 cm) appeared to result in gentler drying conditions, leading to better retention of the natural colour and pigment integrity. In contrast, longer electrode distances (5 cm and 7 cm) likely caused more intense drying conditions, which resulted in greater colour degradation. The results support the idea that EHD drying, particularly at shorter electrode distances, is effective in preserving the colour quality of food products like turmeric, as it minimizes colour loss and maintains the appearance of the dried turmeric slices. Saha, G et. al. (2022) has also investigated the influence of various drying methods on turmeric rhizomes' color, including lightness (L*), redness (a*), and yellowness (b*) and our data well-aligns with the same. Refer to Table 2.2 for the detailed values.

2.6 Water Activity

The results indicate that the activity of dried turmeric samples varied slightly with changes in electrode distance and voltage. The highest activity (0.568) was observed at the 5 cm electrode distance, where the voltage was 17 kV and no air velocity was applied. This suggests that the lower voltage at this distance might have been optimal for maintaining the activity of the turmeric, potentially due to a more balanced drying effect. At the 7 cm distance, the activity was slightly lower (0.562), which could be due to the higher voltage (24kV) applied, possibly causing more intense drying conditions that may affect the retention of active compounds.

The lowest activity (0.548) was found at the 3 cm distance, where a voltage of 14V and air velocity of 0.25 were applied. This lower activity could indicate that the corona wind at this distance was less effective in maintaining the bioactivity of the turmeric, possibly due to increased moisture loss or less uniform drying conditions. The absence of air velocity at the 5 cm distance might have resulted in gentler drying conditions, which could be beneficial for preserving the turmeric's bioactivity. Kumar, P., et. al. (2019) has made the similar observations in drying of turmeric slices. The specific values of trials are provided in Table 2.1.

2.7 Curcumin Content

The curcumin content in fresh and rehydrated electrohydrodynamically (EHD) dried turmeric slices was measured at three different electrode distances: 7 cm, 5 cm, and 3 cm. The results showed a slight increase in curcumin content as the electrode distance decreased, with values of 8.47% at 7 cm, 8.69% at 5 cm, and 8.85% at 3 cm. Statistically, there was no significant difference ($p < 0.05$) in curcumin content between the fresh and EHD dried samples at the 3 cm distance, suggesting that the drying process at this distance was effective in preserving the curcumin content. On the other hand, at the 5 cm and 7 cm distances, a significant reduction in curcumin content was observed compared to the fresh samples, indicating that the intensity of the corona wind at these longer distances may have caused greater degradation of curcumin. This degradation could be attributed to the higher heat and moisture loss at the larger electrode distances. Detailed values are as quoted in table 2.1.

The results are well-aligned with research done by Kaya G., et al. (2020) showing curcumin retention in turmeric slices. Which highlights the importance of shorter electrode distances for retaining bioactive compounds such as curcumin during EHD drying. The enhanced preservation of curcumin at the 3 cm distance supports the notion that EHD drying, being a non-thermal drying method, is particularly advantageous for preserving sensitive compounds. This finding aligns with previous studies suggesting that minimizing exposure to heat and moisture loss is crucial for maintaining the quality and bioactivity of compounds like curcumin during drying.

Table 2.1 Physiochemical parameters of EHD dried turmeric.

Parameter	**Electrode Distance (7 cm) Applied voltage – 24 kV**	**Electrode Distance (5 cm) Applied voltage – 17 kV**	**Electrode Distance (3 cm) Applied voltage – 14 kV**
Bulk Density (kg/m³)	384.59	384.81	385.92
True Density (kg/m³)	1108.45	1113.70	1117.41
Porosity (%)	65.30	65.34	65.49
Shrinkage Ratio (%)	67.133	67.276	68.531
Rehydration Ratio	306	313	312
Water Activity (a_w)	0.562	0.568	0.548
Curcumin Content (%)	8.47	8.69	8.85

Table 2.2 Colour parameters of fresh and dried turmeric.

		L*	**a***	**b***	**Chroma (C)***	**Hue Angle (h°)**	**ΔE**
Fresh		53.62± 2.41	18.00± 3.01	59.91± 2.36	62.55± 1.45	1.279± 0.2	2.50
EHD Dried	**Electrode Distance - 7 cm Applied voltage – 24 kV**	60.73± 2.41	23.11± 3.01	55.91± 2.36	60.49 ± 1.59	1.179 ± 0.2	2.573
	Electrode Distance - 5 cm Applied voltage – 17 kV	58.21± 3.49	25.52± 3.41	53.73± 2.41	59.483 ± 1.59	1.137 ± 0.12	2.454
	Electrode Distance - 3 cm Applied voltage – 14 kV	65.73± 2.98	21.39± 2.43	46.23± 2.21	50.939 ± 1.42	1.137 ± 0.18	2.388

CONCLUSION

The results of this study reveal the impact of electrohydrodynamic (EHD) drying parameters, including electrode distance, voltage, air velocity, and temperature, on various physical and chemical properties of turmeric slices. The bulk and true density values showed minimal changes across the different electrode distances, suggesting that the drying process does not significantly affect the overall packing density of the turmeric. However, the true density increased slightly with decreasing electrode distance, indicating subtle alterations in the internal structure of the material.

Porosity, shrinkage ratio, and rehydration ratio remained relatively stable across the different electrode distances, with small variations observed, especially at the 3 cm distance. These results demonstrate that the EHD drying process effectively maintains the structural integrity and porosity of the turmeric slices while promoting efficient moisture removal. The rehydration ratio showed a notable decline at longer electrode distances, with the highest ratio observed at the shortest distance, supporting the idea that corona wind penetration influences the formation of a more porous structure that enhances rehydration.

Colour analysis indicated that EHD drying preserved the colour of turmeric slices, with minimal changes in the lightness and colour attributes at the 3 cm distance. The preservation of the reddish and yellowish hues suggests that EHD drying is effective in maintaining the visual quality of turmeric slices, particularly at shorter electrode distances, where less heat is involved.

In terms of bioactive compounds, the curcumin content was best preserved at the 3 cm electrode distance, where no significant degradation was observed. However, at the longer electrode distances (5 cm and 7 cm), a reduction in curcumin content was noted, likely due to more intense drying conditions at these distances. This supports the conclusion that EHD drying, particularly at shorter electrode distances, is advantageous for preserving the bioactive compounds in turmeric.

Overall, EHD drying emerges as a promising non-thermal preservation technique for turmeric, effectively maintaining key physical, chemical, and bioactive properties while minimizing losses in quality. The findings suggest that shorter electrode distances may offer optimal conditions for preserving turmeric's structure, colour, and bioactive compounds, thus providing insights into improving the quality of dried turmeric for culinary and medicinal purposes.

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